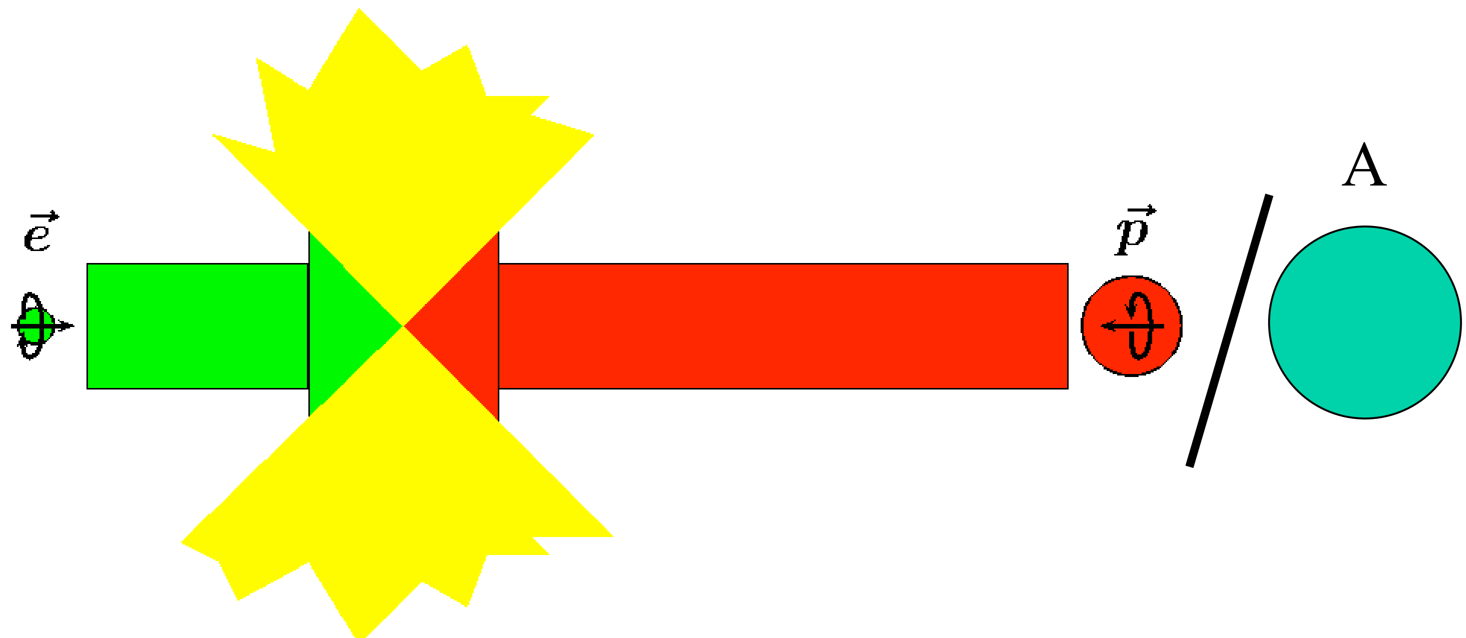
eRHIC: The Collider, The Detector & Low x Issues



Forward Physics at RHIC Workshop
RHIC AGS USER'S MEETING
May, 14 2004

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Stony Brook University
RBRC

STONY BROOK STATE UNIVERSITY OF NEW YORK

Some spin & Low x-high Q^2 surprises…

- Stern & Gehrlach (1921) Space quantization associated with direction
- Goudschmidt & Ulhenbeck (1926): Atomic fine structure & electron spin magnetic moment
- Stern (1933) Proton anomalous magnetic moment 2.79 μ_N
- Kusch(1947) Electron anomalous magnetic moment 1.00119μ_0
- Prescott & Yale-SLAC Collaboration (1978) EW interference in polarized e-d DIS, parity non-conservation
- **European Muon Collaboration (1988/9) Spin Crisis/Puzzle**

Transverse single spin asymmetries:

E704, AGS pp scattering, HERMES (1990s) RHIC Spin (2001)

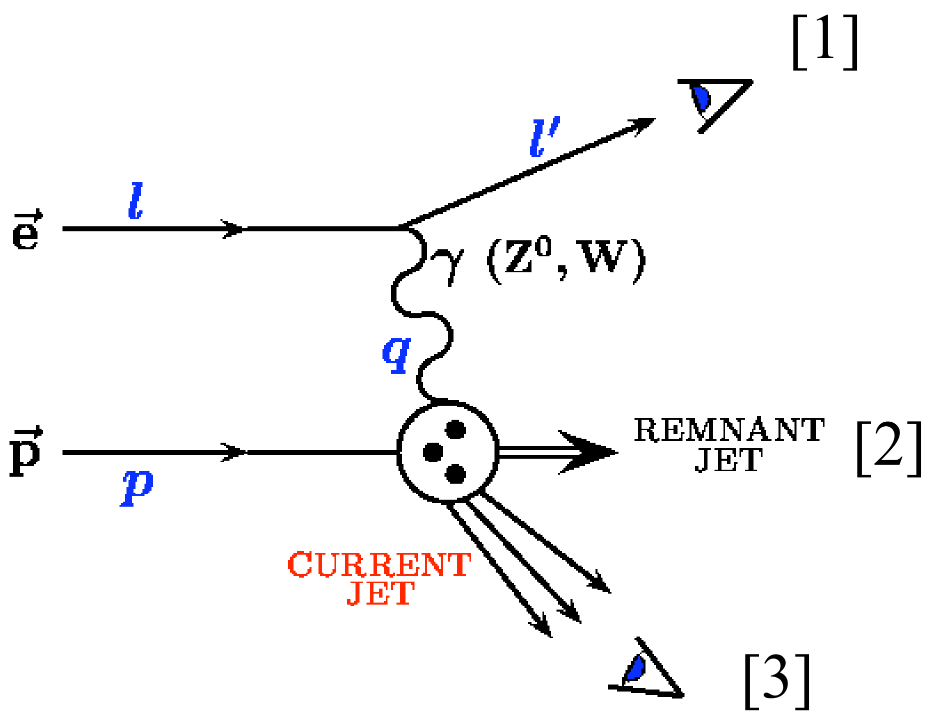
>> single spin neutron production(PHENIX)

>> pion production (STAR) at 200 GeV Sqrt(S)

- Elastic e-p scattering at SLAC (1950s) → Q2 ~ 1 GeV2 ➔ Finite size of the proton
- Inelastic e-p scattering at SLAC (1960s)→ Q2 > 1 GeV2 ➔ Parton structure of the proton
- Inelastic mu-p scattering off p/d/N at CERN (1980s) → Q2 > 1 GeV2 ➔ Unpolarized EMC effect, nuclear shadowing?
- Inelastic e-p scattering at HERA/DESY (1990s)→ Q2 > 1 GeV2
  - ➔ Unexpected rise of F2 at low x
  - ➔ Diffraction in e-p
  - ➔ Saturation(??)

A facility that does both would be ideal….

Deep Inelastic Scattering



$$Q^2 = -q^2 = sxy$$

$$x = \frac{Q^2}{2p \cdot q}$$

$$y = \frac{p \cdot q}{p \cdot l}$$

$$s = 4E_e E_p$$

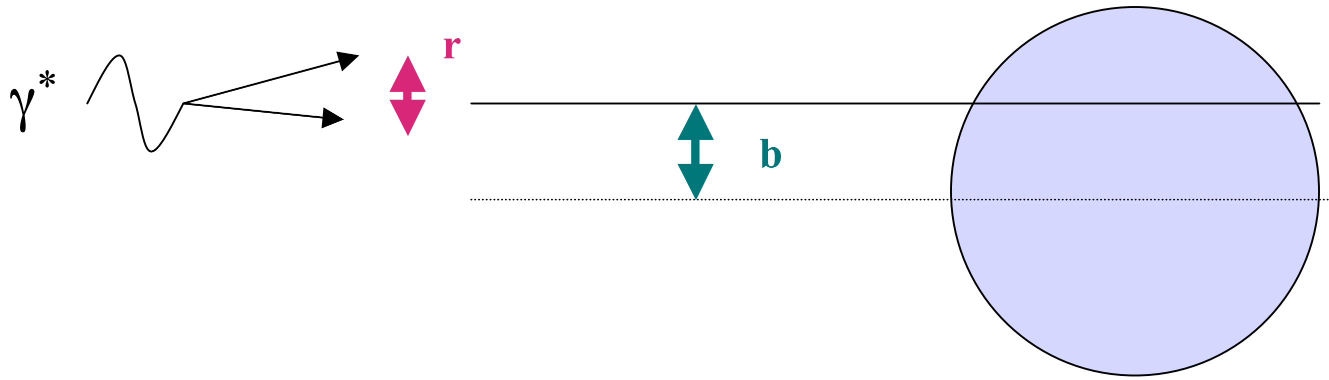
$$W = (q+p)^2$$

- Observe scattered electron/muon & hadrons in current jets
- Observe spectator or remnant jet
  >> suitably designed detector…

Lumi

[1]+[2]+[3]	→	[3] exclusive
[1]+[2]	→	[2] semi-inclusive
[1]	→	[1] inclusive

Physics Picture in Proton Rest Frame



r ~ 0.2 fm/Q (0.02 – 2 fm for $100>Q^2>0.01$ GeV^2) transverse size of probe

ct ~ 0.2 fm ($W^2/2M_PQ^2$) (<1 fm to 1000's fm) – scale over which photon fluctuations survive

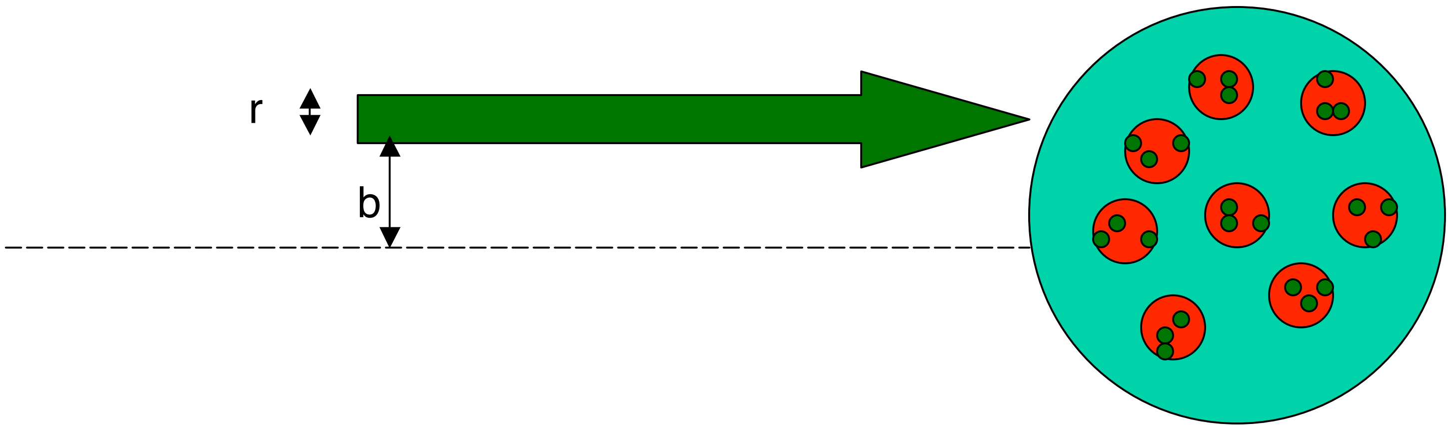
And, in exclusive processes, can vary the impact parameter

b ~ 0.2 fm/sqrt(t) $t=(p-p')^2$

Can control these parameters experimentally !

Precision eA measurements

- **Enhancement of possible nonlinear effects (saturation)**

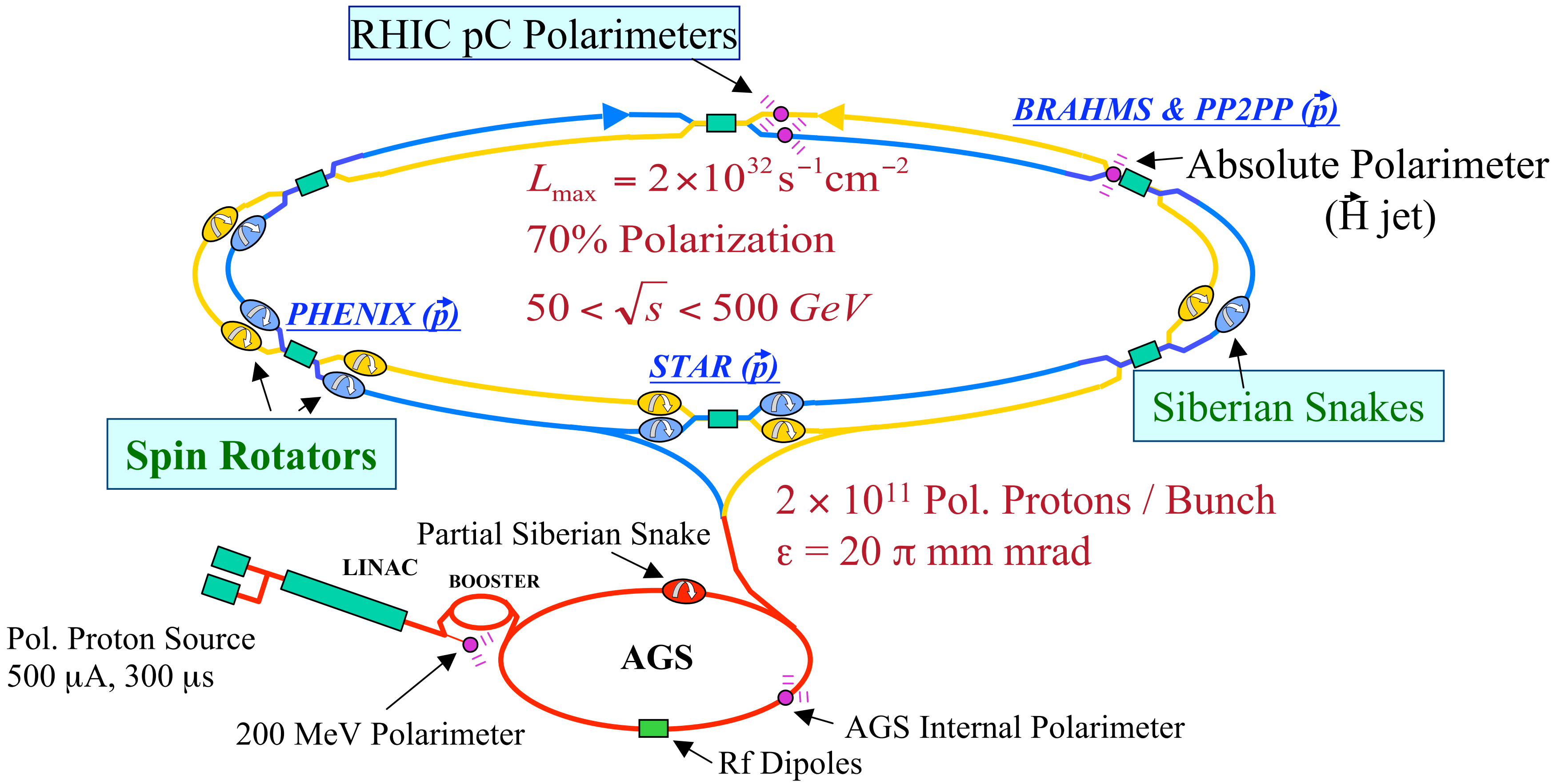


At small x, the scattering is coherent over nucleus, so the diquark sees much larger # of partons:

$xg(x_{eff},Q^2) = A^{1/3}\, xg(x,Q^2)$, at small-x, $xg \;\alpha\; x^{-\lambda}$, so

$$x_{eff}^{-\lambda} = A^{1/3}x^{-\lambda} \quad \text{so} \quad x_{eff} \approx xA^{-1/3\,\lambda} = xA^{-3}\ (Q^2 < 1\ \text{GeV}^2)$$
$$= xA^{-1}\ (Q^2 \approx 100\ \text{GeV}^2)$$

Relativistic Heavy Ion Collider



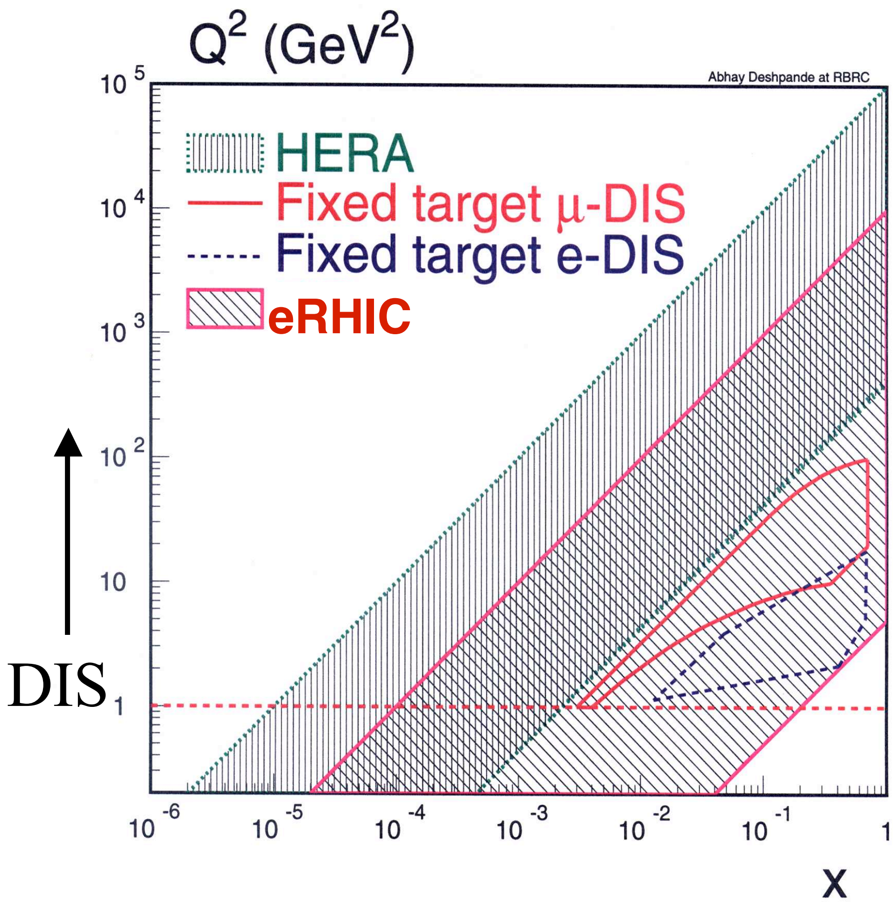
RHIC accelerates heavy ions to 100 GeV/A
and polarized protons to 250 GeV

Proposal under consideration

eRHIC at BNL

A high energy, high intensity polarized electron/positron beam facility at BNL to collide with the existing RHIC heavy ion and polarized proton beam would significantly enhance RHIC's ability to probe fundamental and universal aspects of QCD

eRHIC vs. Other DIS Facilities (I)



- New kinematic region

- E_e = 5-10 GeV
- E_p = 30 – 250 GeV
- Sqrt(s) = ~25 – 100 GeV

- Kinematic reach of eRHIC

  x = 10^{-4} → ~0.7 (Q^2 > 1 GeV^2)

  Q^2 = 0 → 10^4 GeV

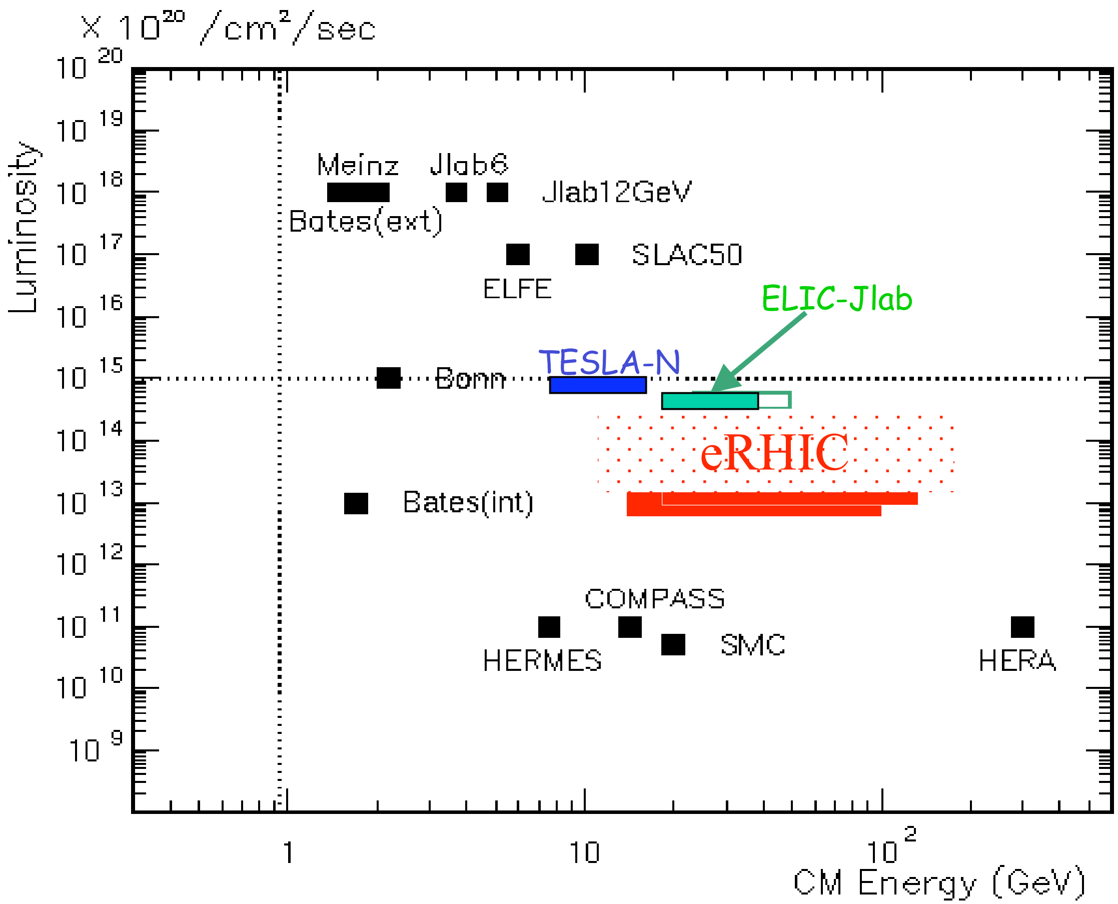
- Polarized e, p and light ion beams -- ~70%

- Heavy ion beams of ALL elements!

- High Luminosity

  L > (at least) 10^{33} cm^{-2} sec^{-1}

eRHIC & ELIC vs. Other DIS Facilities



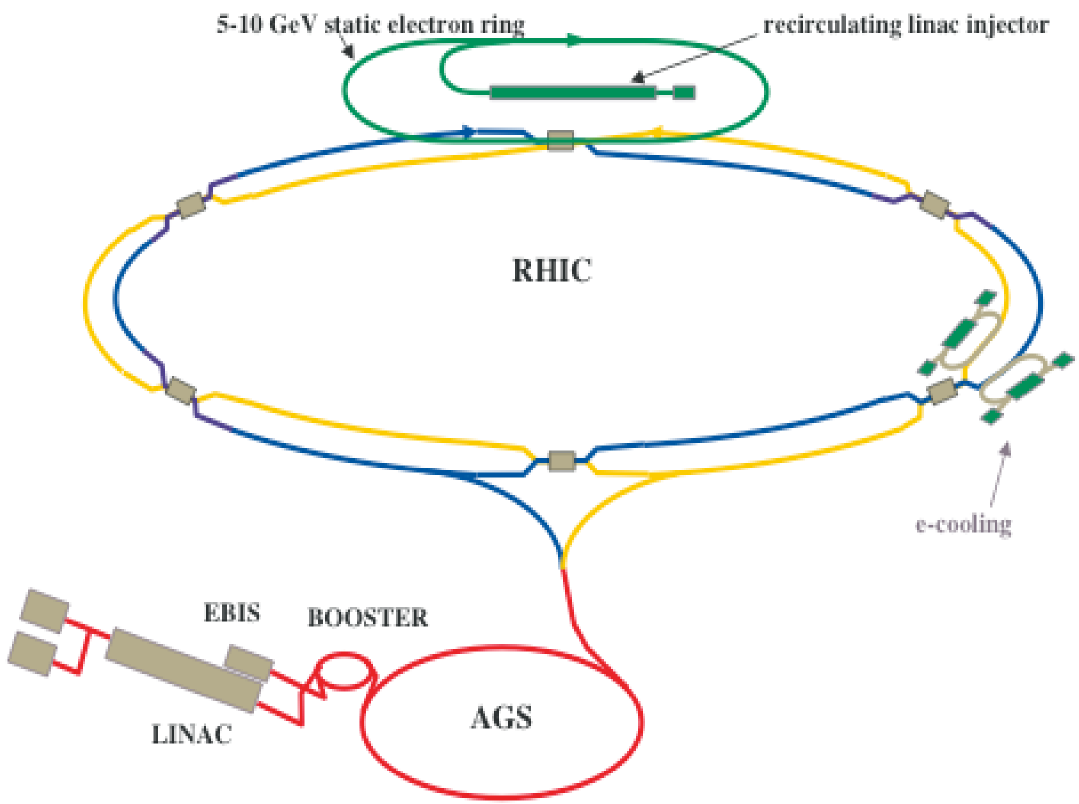
eRHIC:

>> Variable beam energy
>> **p → U hadron beams**
>> Light Ion polarization
>> Large Luminosity
>> **Huge Kinematic reach**

ELIC at Jlab:
(Electron-Light Ion Collider)

>> Variable beam energy
>> Light Ion polarization
>> **Huge Luminosity**

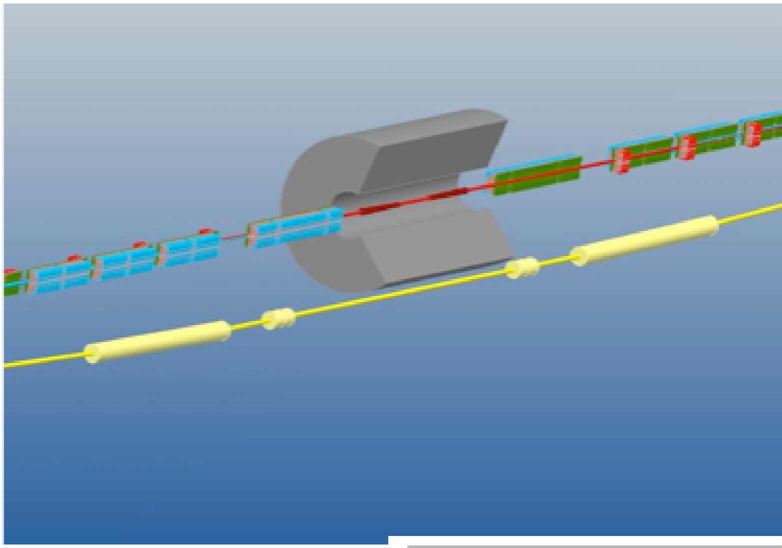
The eRHIC Ring-Ring Lay Out & Plans

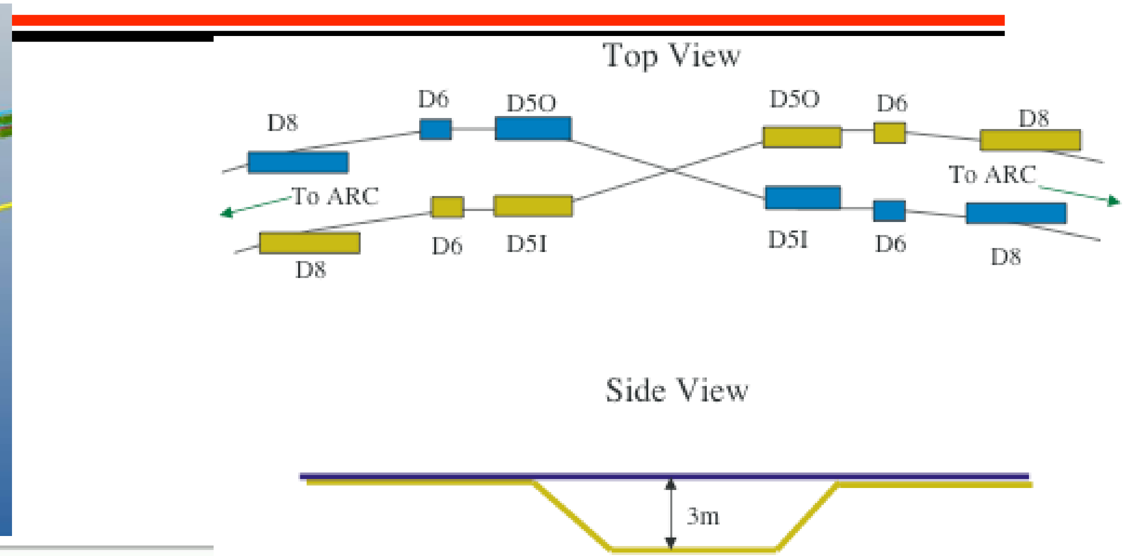


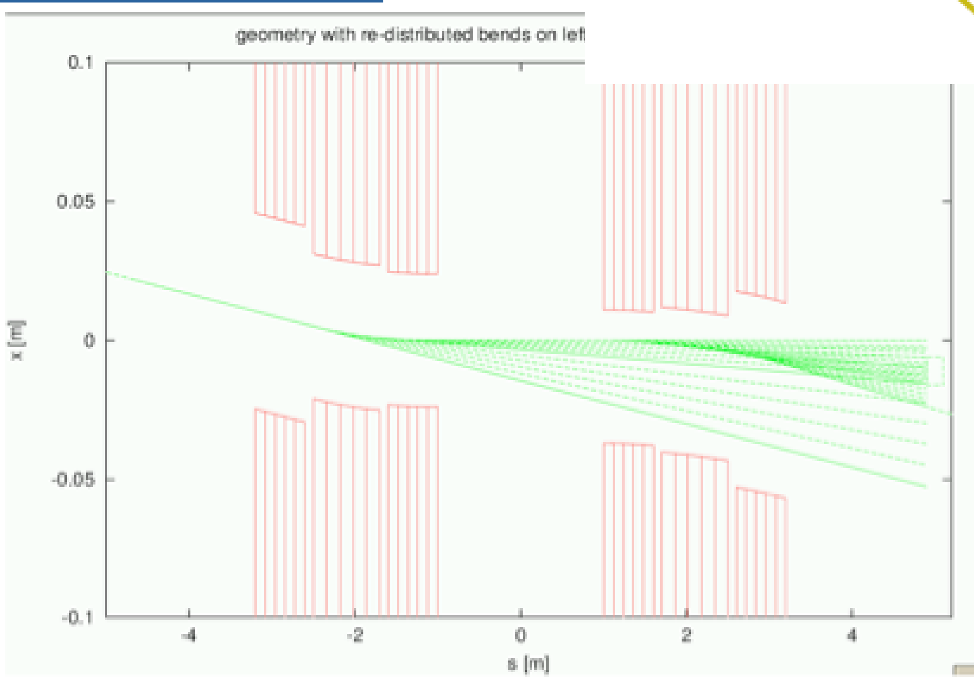
- Full energy injection
- Polarized e- source & unpolarized e+ --> (polarization via synchrotron radiation)
- 10 GeV main design but up to 5 GeV reduction possible with **minimal polarization loss**
- Fill in bunch spacing 35ns

Present conservative estimates L_(ep)~ 4 x 10^{32} cm^{-2} sec^{-1} **work on luminosity enhancement continues**. *Advantages:* both positrons/electrons positrons….. *Disadvantages:* Multiple detectors or/and Interaction Regions?

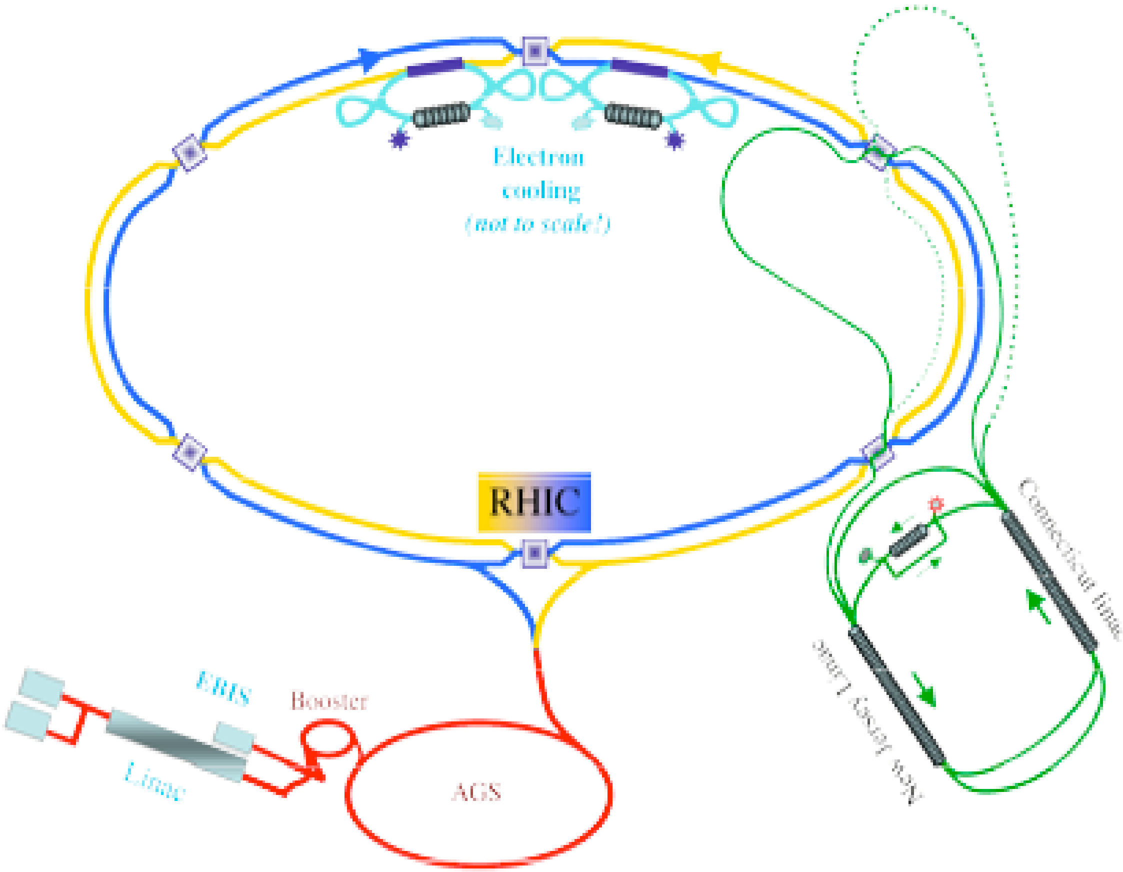
IR, Synchrotron Radiation, other Hadron Beam Modification







eRHIC: Linac-Ring Option



Features:

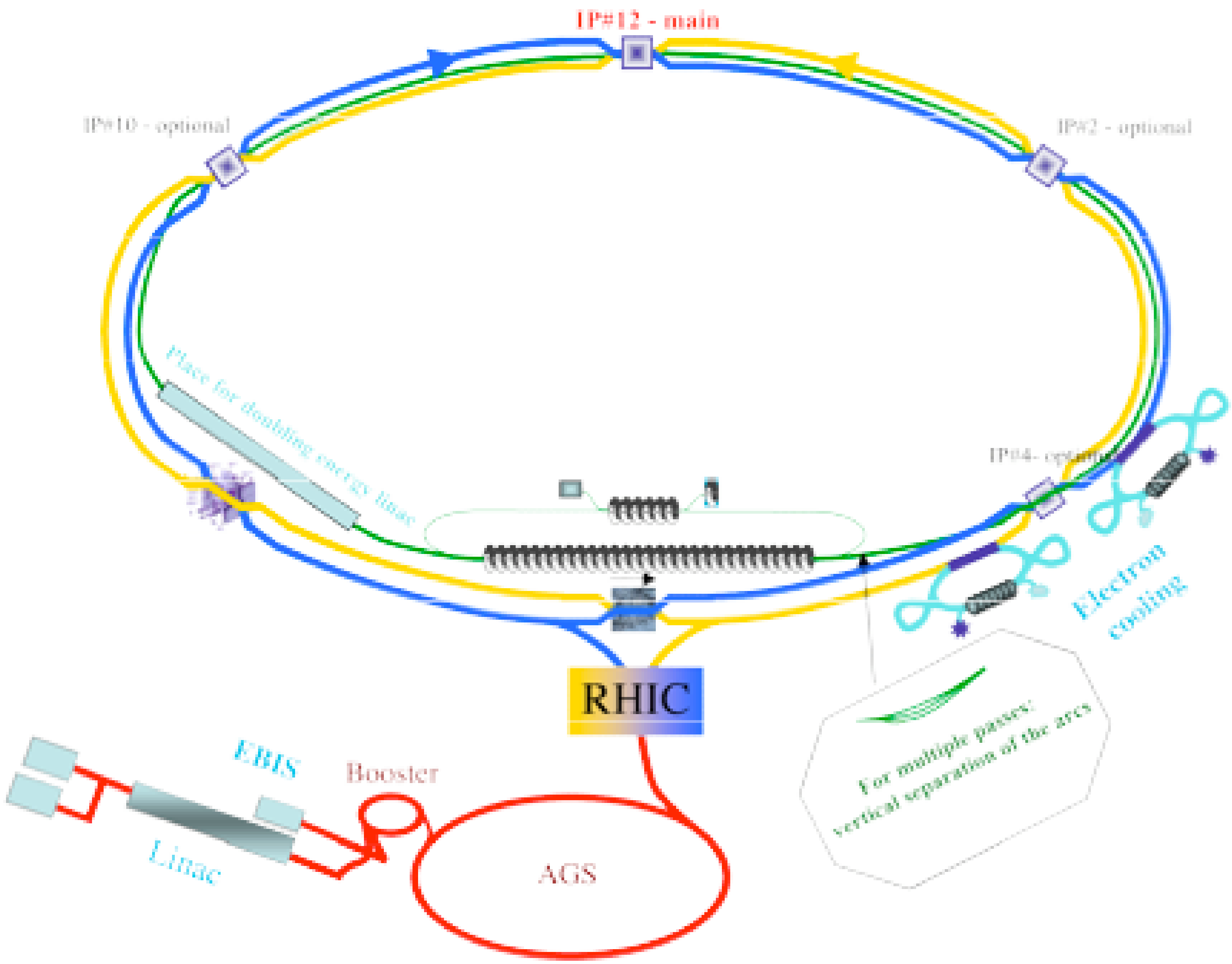
- Up to L(ep) ~10^{34} cm^{-2}sec^{-1}
- Polarization transparency at all energies
- Multiple IRs and detectors
  - Long element free regions
- STAR & PHENIX still run
- Full range of CM Energies
- Future upgrades to 20 GeV seem straightforward

Limitations:

Positron beams not possible

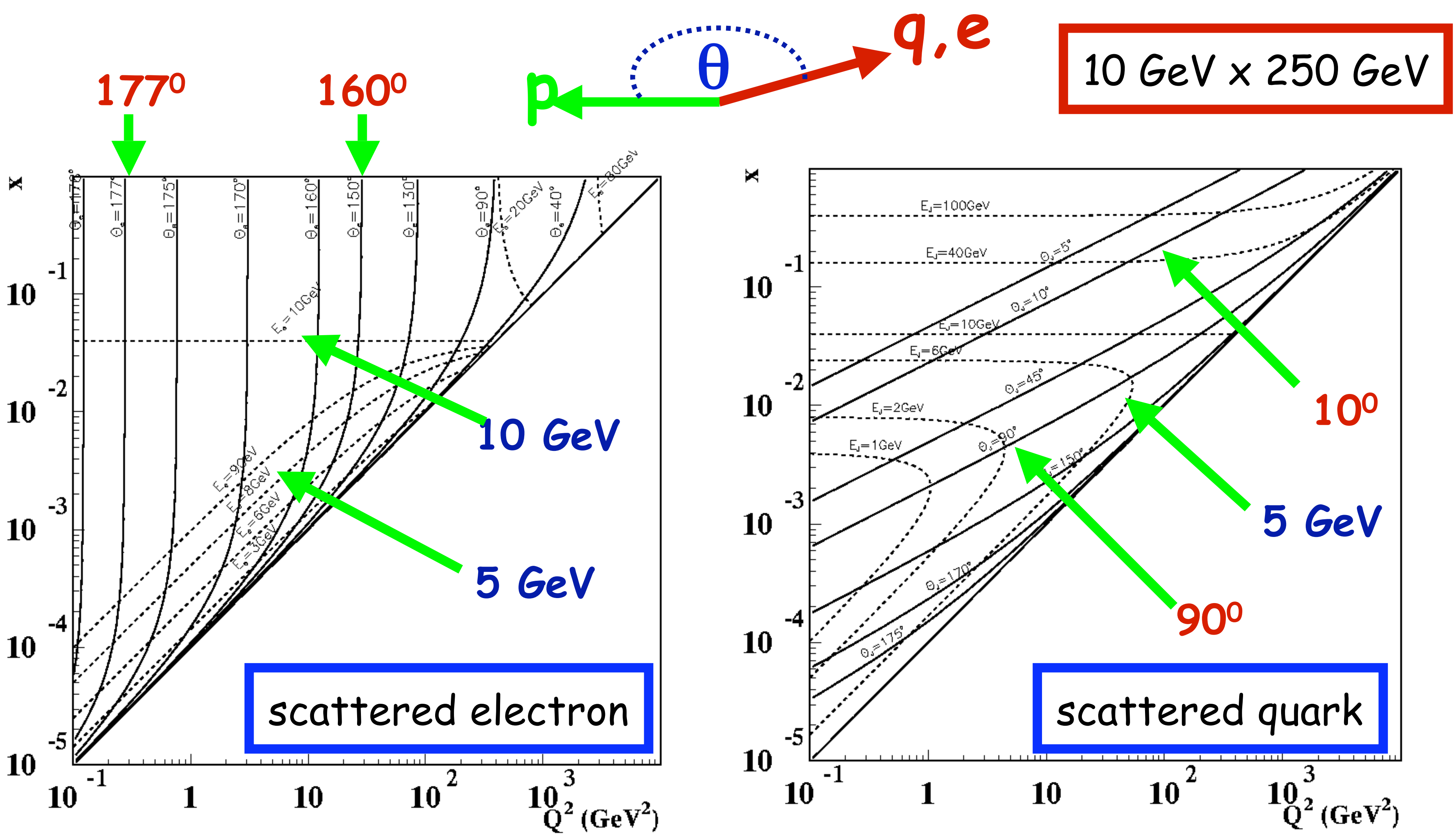
Physics implications?

eRHIC Linac-Ring

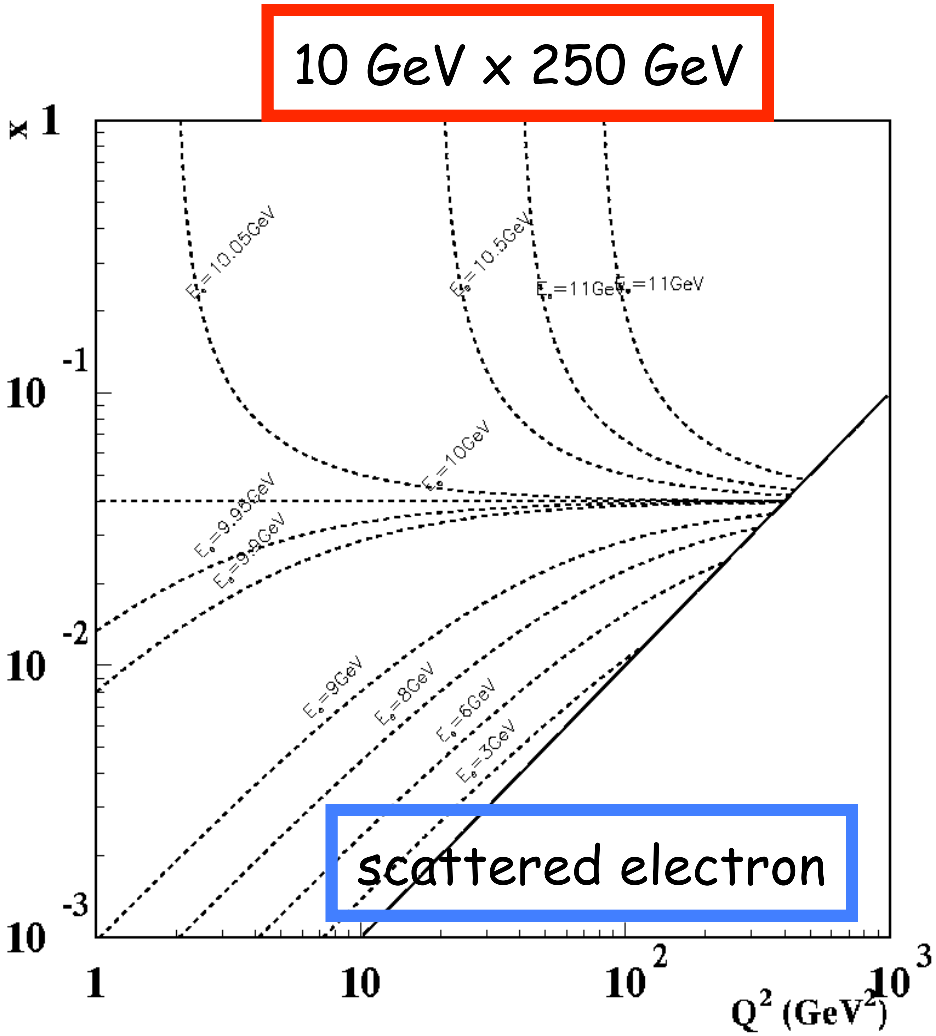


Up to 4 Irs
Up to 20 GeV
Electron beams

Where do electrons and quarks go?



Electron kinematics… some details…



At HERA:

→Electron method: $\Delta x/x \sim \Delta E/(y.E)$
Limited by calorimeter resolution

→Hadron method:
Limited by noise in calorimeter
(E_noise/E_beam)

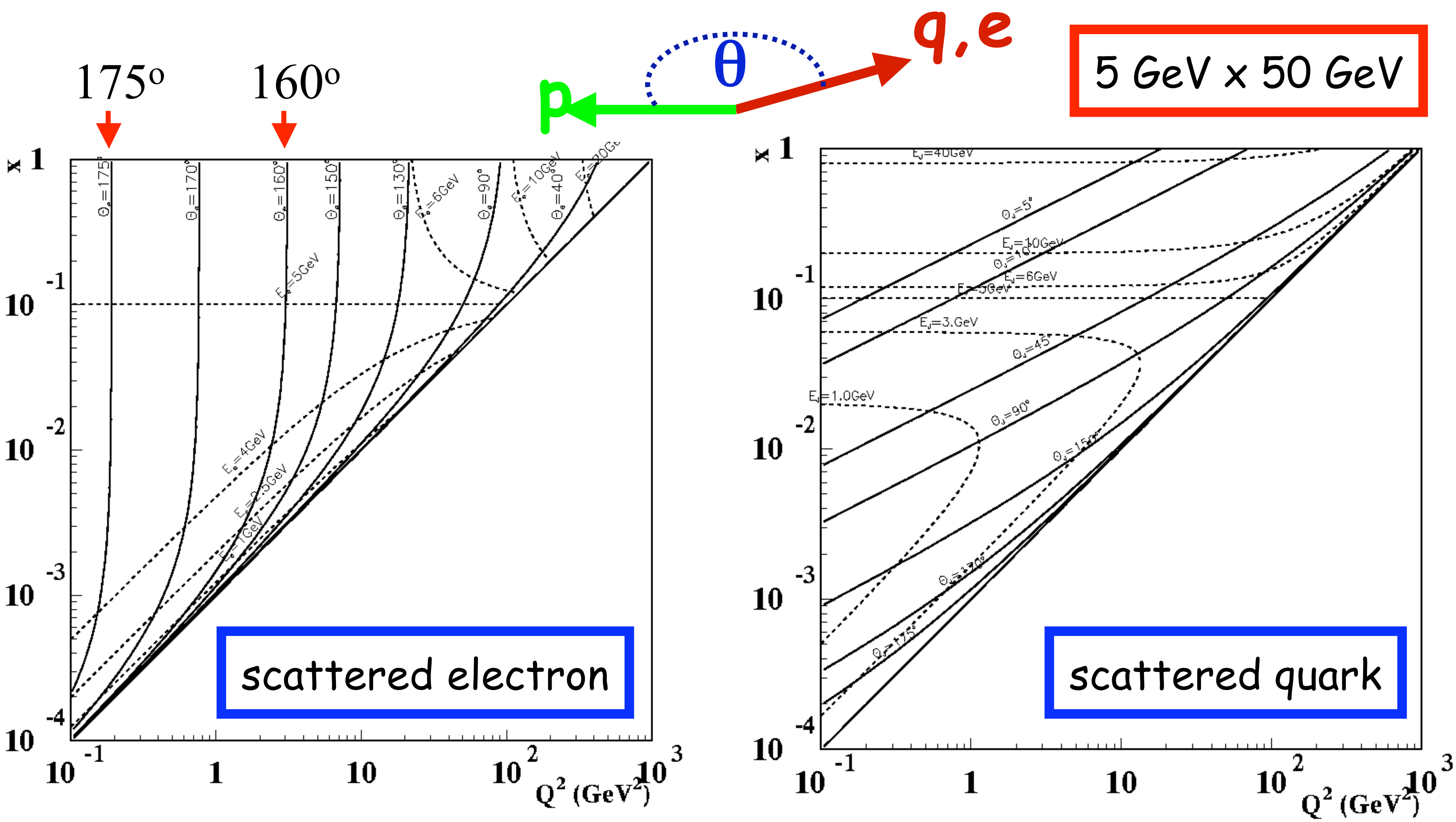
At eRHIC:

→Measure electron energy with
tracker (< 20 GeV, large kin. region)
$\Delta p/p \sim 0.005\text{-}0.0001$ →(2-4T Magnet)

→Design low noise calorimeter

→Crystal or SPACAL

Electron, Quark Kinematics



Scientific Frontiers Open to eRHIC

- **Nucleon Structure:** polarized & unpolarized e-p/n scattering

  -- Role of quarks and gluons in the nucleon

  >> Unpolarized quark & gluon distributions, confinement in nucleons

  >> Spin structure: polarized quark & gluon distributions

  -- Correlation between partons

  >> hard exclusive processes leading to Generalized Parton Distributions (GPD's)

- **Meson Structure:**

  -- Mesons are goldstone bosons and play a fundamental role in QCD

- **Nuclear structure:** unpolarized e-A scattering

  -- Role of quarks and gluons in nuclei, confinement in nuclei

  -- e-p vs. e-A physics in comparison and variability of A: from d→U

- **Hadronization in nucleons and nuclei & effect of nuclear media**

  -- How do partons knocked out of nucleon in DIS evolve in to colorless hadrons?

- **Partonic matter under extreme conditions**

  -- e-A vs. e-p scattering; study as a function of A

Unpolarized DIS e-p at eRHIC

- Large(r) kinematic region already covered at HERA but additional studies at eRHIC are possible & desirable
- Uniqueness of eRHIC: high luminosity, variable Sqrt(s), He3 beam, improved detector & interaction region
- Will enable precision physics:

-- He3 beams → neutron structure → d/u as x→0,
dbar(x)-ubar(d) [1]

-- precision measurement of $\alpha_S(Q^2)$ [1]

-- precision photo-production physics [1]

-- precision gluon distribution in x=0.001 to x=0.6 [1]

$\boxed{\text{-- slopes in } dF_2/d\ln Q^2 \text{ (Transition from QCD --> pQCD)}}$ [1]

-- flavor separation (charm and strangeness) [2]

-- exclusive reaction measurements [2,3]

-- nuclear fragmentation region measurements [2,3]

Luminosity Requirement

Polarized DIS at eRHIC

- Spin structure functions g_1 (p,n) at low x, high precision [1]
  -- g_1(p-n): Bjorken Spin sum rule better than 1-2% accuracy
- Polarized gluon distribution function $\Delta G(x,Q^2)$ [1]
  -- at least three different experimental methods
- Precision measurement of $\alpha_S(Q^2)$ from g_1 scaling violations [1]
- Polarized s.f. of the photon from photo-production [1]
- Electroweak s. f. g_5 via $W^{+/-}$ production [1,2]
- Flavor separation of PDFs through semi-inclusive DIS [1]
- Deeply Virtual Compton Scattering (DVCS) [1,2]
  >> Gerneralized Parton Distributions (GPDs) [3]
- Transversity [1]
- Drell-Hern-Gerasimov spin sum rule test at high ν [1]
- Target/Current fragmentation studies [2,3]
- … etc….

Luminosity Requirement

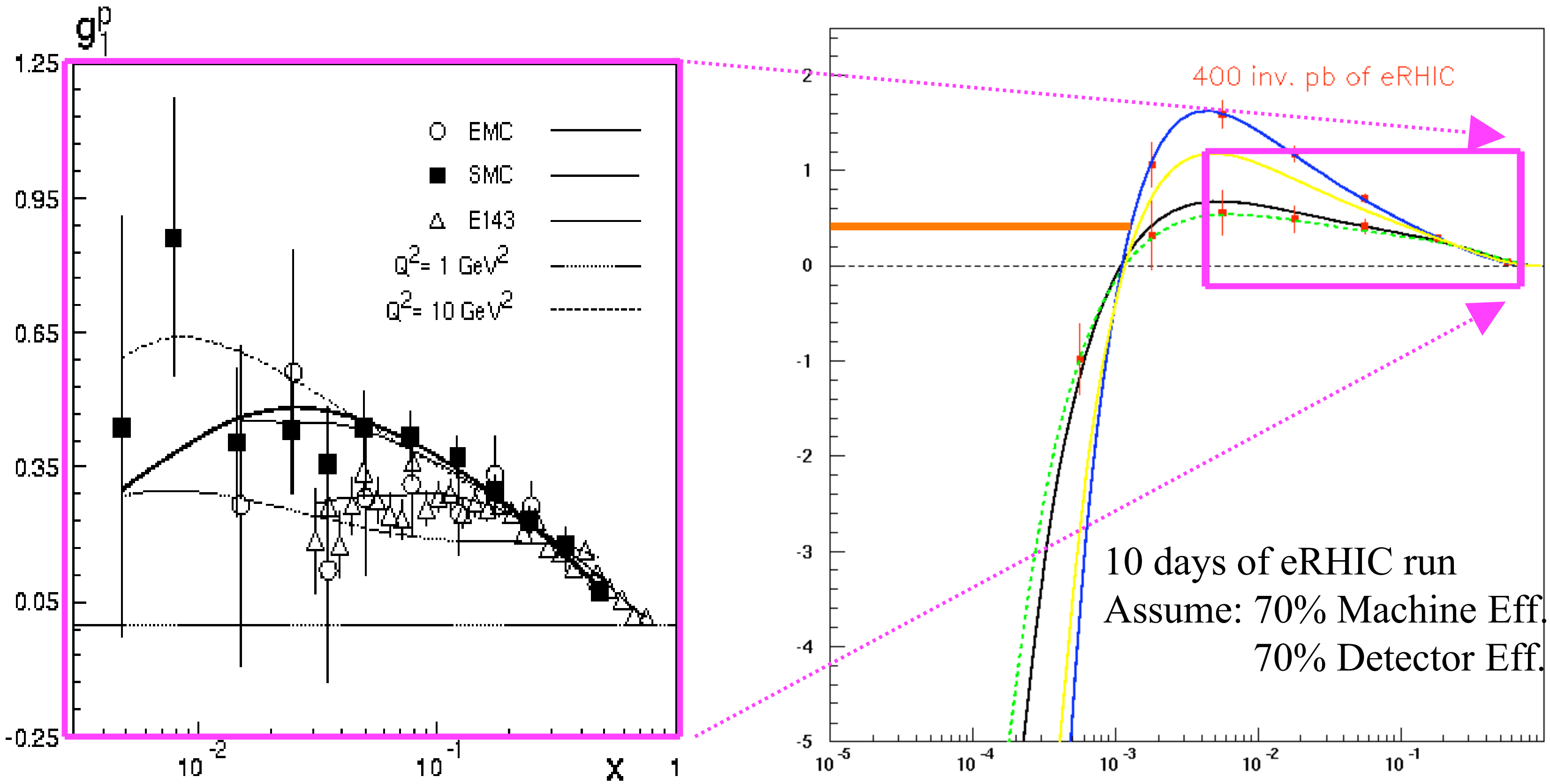
Proton $g_1(x,Q^2)$ low x eRHIC

Fixed target experiments

1989 – 1999 Data

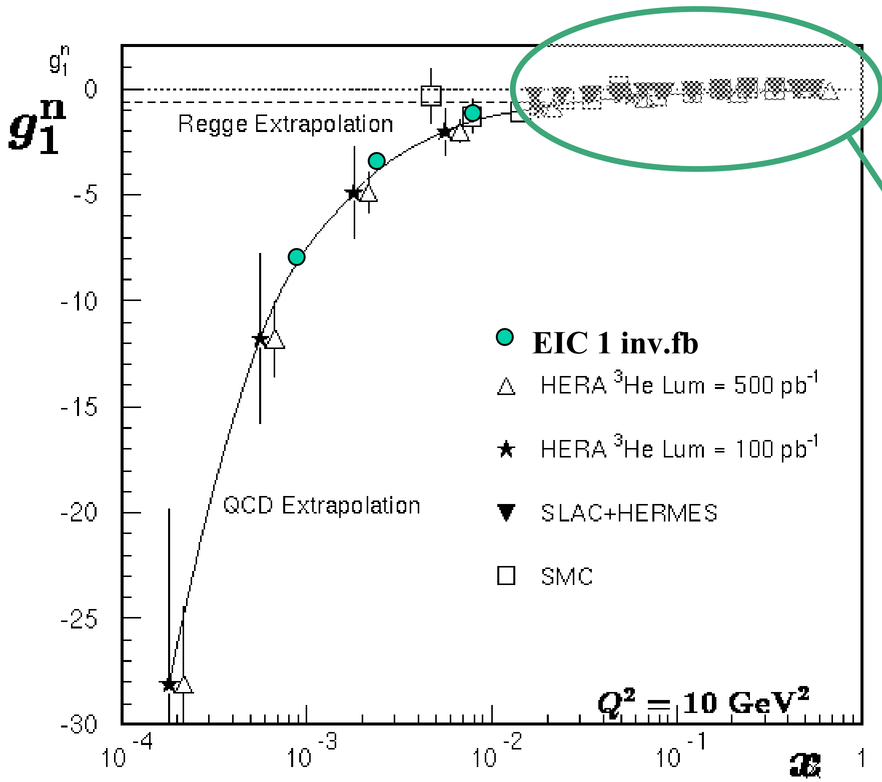
eRHIC 250 x 10 GeV

Luminosity = ~85 inv. pb/day



Studies included statistical error & detector smearing to confirm that asymmetries are measurable. No present or future approved experiment will be able to make this measurement

Low x measurement of g_1 of Neutron



- With polarized He3
- ~ 2 weeks of data at eRHIC
- Compared with SMC(past)
- **If combined with g1 of proton results in Bjorken sum rule test of better than 1-2% within a couple of months of running**

Highlights of e-A Physics at eRHIC

- Study of e-A physics in Collider mode for the first time
- QCD in a different environment

- Clarify & reinforce physics studied so far in fixed target e-A & μ-A experiments including target fragmentation

  QCD in: $x > [1/(2m_N R_N)] \sim 0.1$ (high x)

  QCD in: $[1/(2m_N R_A)] < x < [1/(2m_N R_N)] \sim 0.1$ (medium x)

  Quark/Gluon shadowing

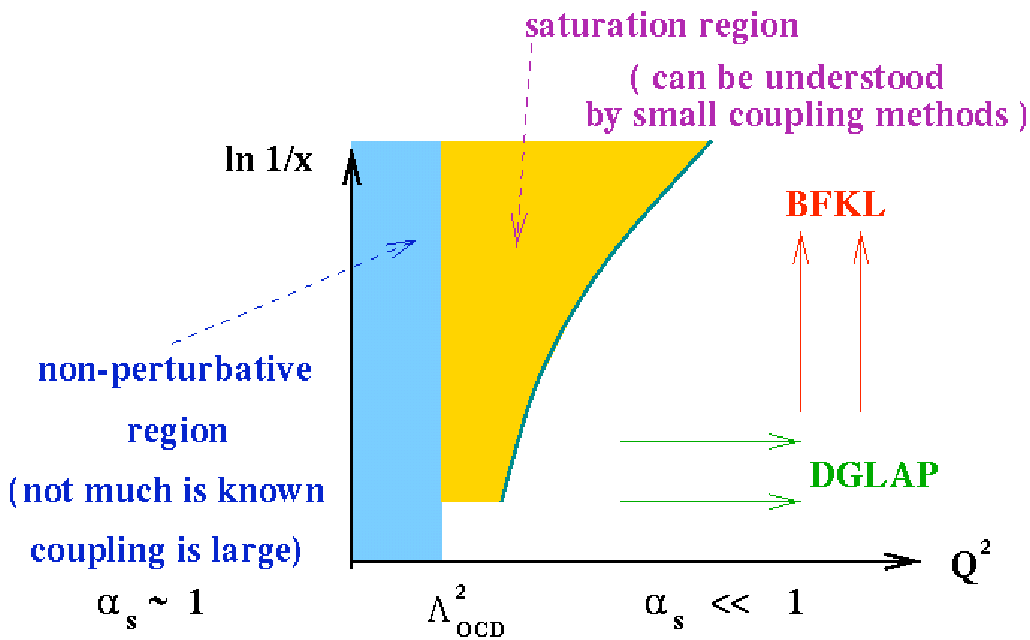
  Nuclear medium dependence of hadronization

- …. And extend in to a very low x region to explore:

  saturation effects or high density partonic matter also called the Color Glass Condensate (CGC)

  QCD in: $x < [1/(2m_N R_A)] \sim 0.01$ (low x)

The Saturation Region…

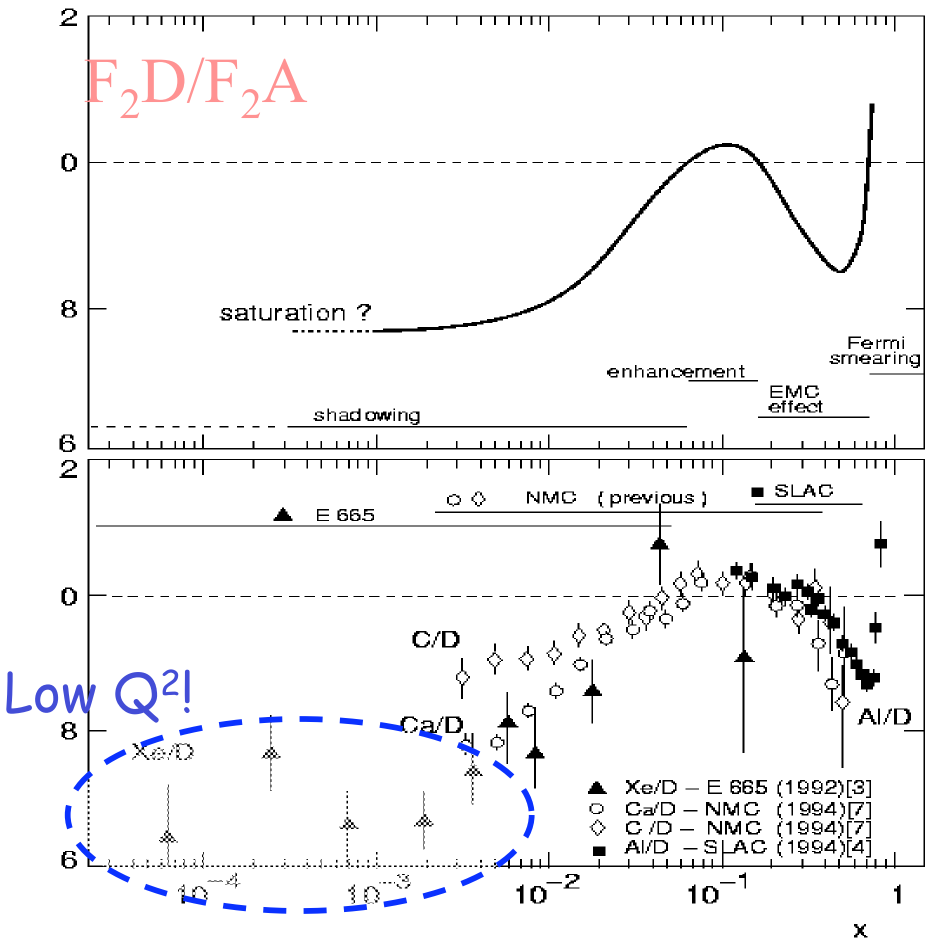


- As parton densities grow, standard pQCD break down.
- Even though coupling is weak, physics may be non-perturbative due to high field strengths generated by large number of partons.
- A new state of matter???

An e-A collider/detector experiment with high luminosity and capability to have different species of nuclei in the same detector would be ideal… ➔ Need the eRHIC at BNL

E665, NMC, SLAC Experiments

DIS in Nuclei is Different!



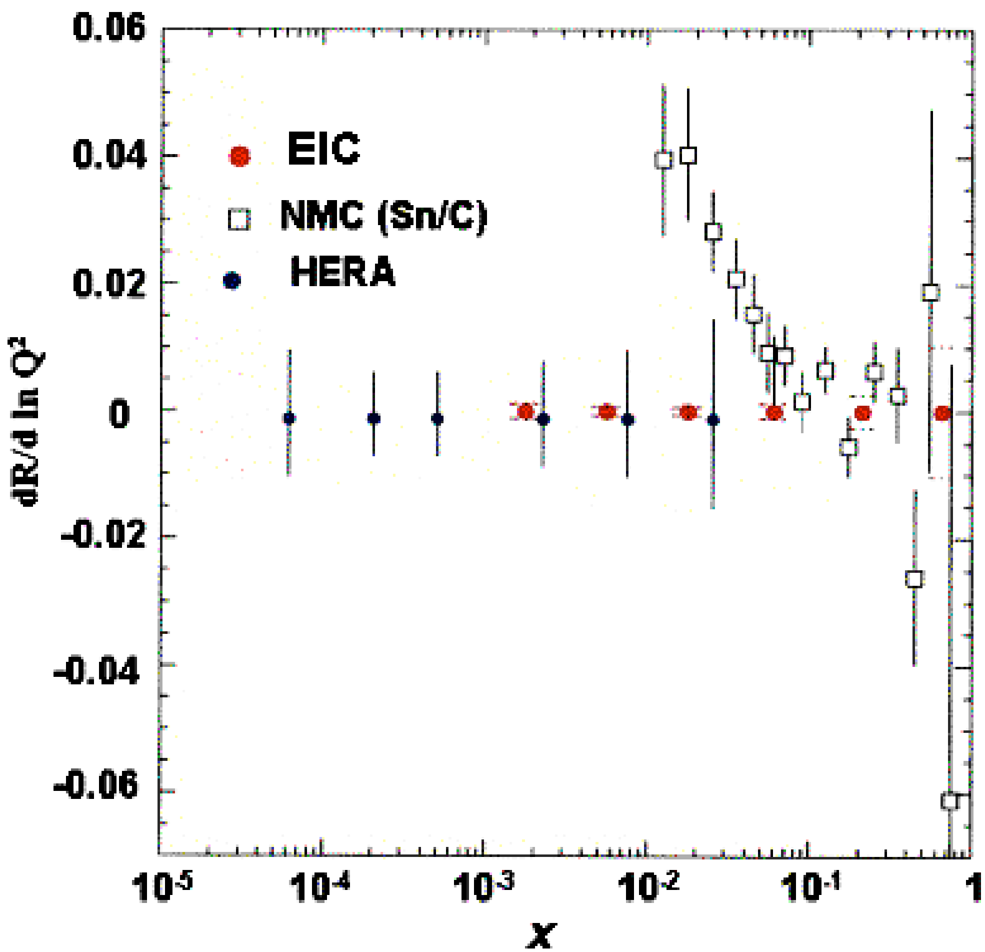
Regions of:

- Fermi smearing
- EMC effect
- Enhancement
- Shadowing
- Saturation?

Regions of shadowing and saturation mostly around $Q^2 \sim 1$ GeV^2

An e-A collision at eRHIC can be at significantly higher Q^2

Statistical Precision at eRHIC for e-A



- High precision at EIC shown statistical errors for 1 pb^{-1}
- Recall: eRHIC will ~85 pb^{-1} per day
- NMC data F_2(Sn/D)
- EIC's Q^2 range between 1 and 10 GeV^2
- Will explore saturation region!

Signatures of Saturation/CGC (I)

- Structure functions $F_2(x,Q^2)$, $dF_2/d\ln Q^2$, $dF_2/d\ln x$
  - $dF_2/d\ln Q^2$ at fixed x at high Q^2 is the gluon distribution
  - CGC vs. conventional pQCD predict very different
  - Gluon measurements using semi-inclusive… di-jet final states
  - eRHIC will differentiate them easily for protons and heavy nuclei

- Longitudinal structure function $F_L = F_2 - 2xF_1$
  - Provide independent gluon distribution measurement
  - Needs variable electron beam (sqrt(s)) energy → Possible at eRHIC

- Measurement of nuclear shadowing
  - Quark shadowing ($F_2^A/A*F_2^N$) in fixed target experiments observed
  - Gluon shadowing ($G^A/A*G^N$) indirect evidence only… pQCD at NLO
  - This is expected to be severe at low x and high Q^2
  - Ideal measurement for eRHIC

Signatures of CGC (II)

- Shadowing and diffraction:

Relation between nuclear shadowing and diffraction will be very different at high parton density media… eRHIC will study this systematically as a function of A of the nuclei.

Will need special considerations in detector design for diffractive physics: "FORWARD" physics

$$e + A \rightarrow e' + \gamma^* + A \rightarrow e' + X + A; \; M_X^2 >> \Lambda_{QCD}^2$$

- Hard Diffraction

Large rapidity gap between current and target fragmentation region. At HERA 7% cross section diffractive.

In e-A at eRHIC, diffractive processes may contribute 30-40% to the total cross section.

- Coherent & Inclusive vector meson production:

For light vector mesons diff. Cross section. = 0.5 (inclusive)

Heavy vector mesons this decreases…finally reaching 1/lnQ2

eRHIC will measure for different nuclei, $\rho,\omega,\phi,J/\psi,\Upsilon$ cross sections

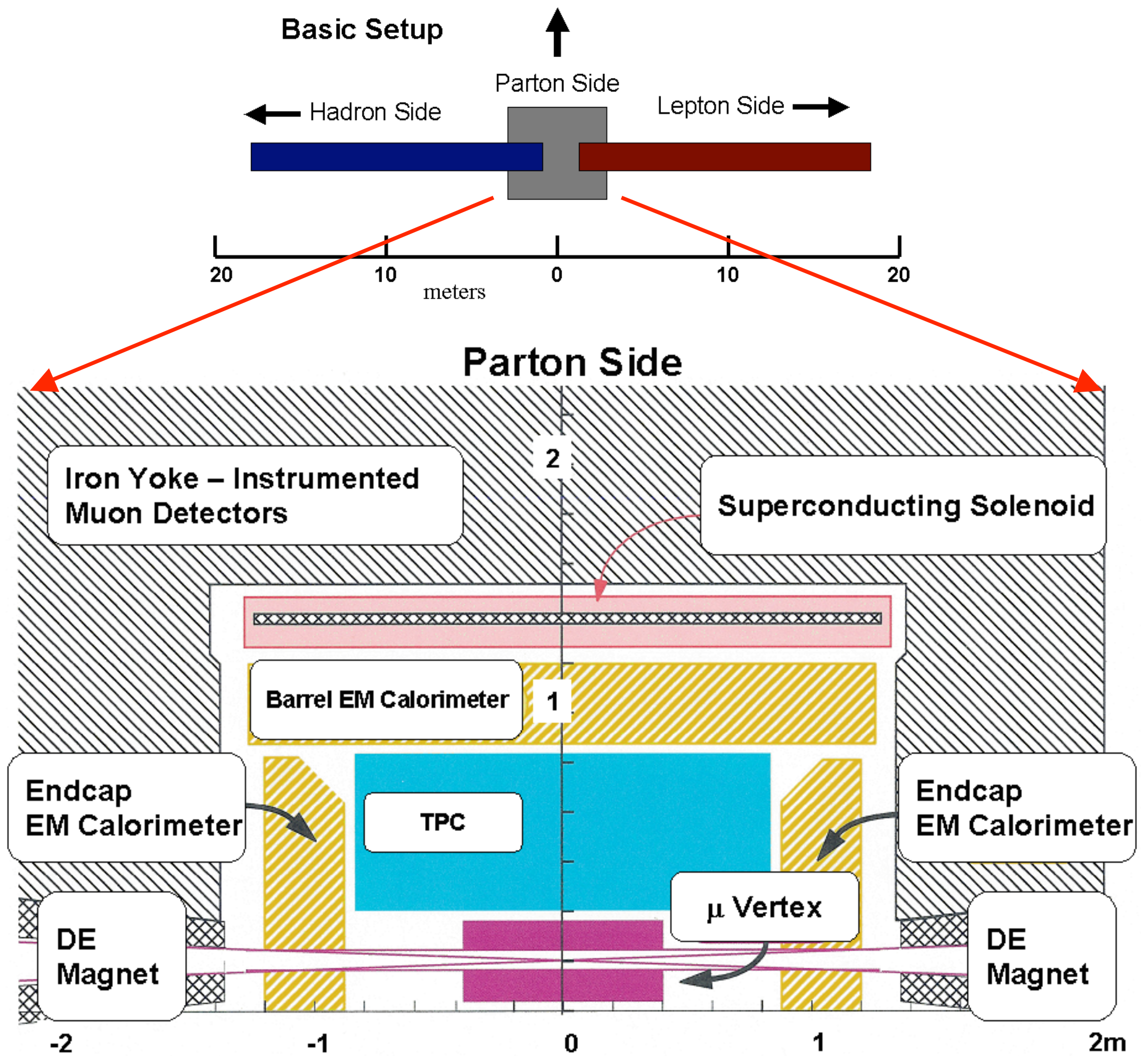
A Detector for eRHIC → A 4π Detector

- Scattered electrons to measure kinematics of DIS
- Scattered electrons at small (~zero degrees) to tag photo production
- Central hadronic final state for kinematics, jet measurements, quark flavor tagging, fragmentation studies, particle ID
- Central hard photon and particle/vector-meson detection (DVCS)
- ~Zero angle photon measurement to control radiative corrections and in e-A physics to tag nuclear de-excitations
- Missing E_T for neutrino final states (W decays)
- Forward tagging for 1) nuclear fragments, 2) diffractive physics

- "At least one" second detector could be "rolled" in from time to time….
  …under consideration(?) A second interaction point(?).
  ==> To be decided based on physics case and the technology status at a later date

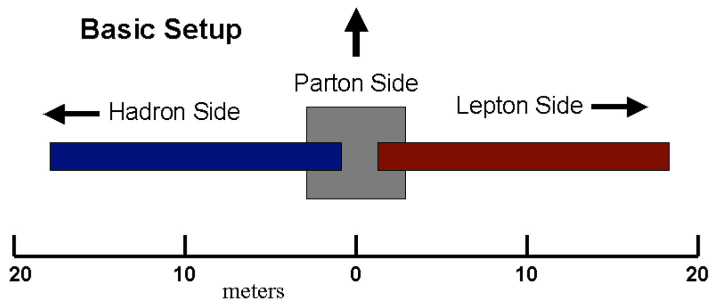
- eRHIC will provide: 1) Variable beam energies 2) different hadronic species, some of them polarization, 3) high luminosity

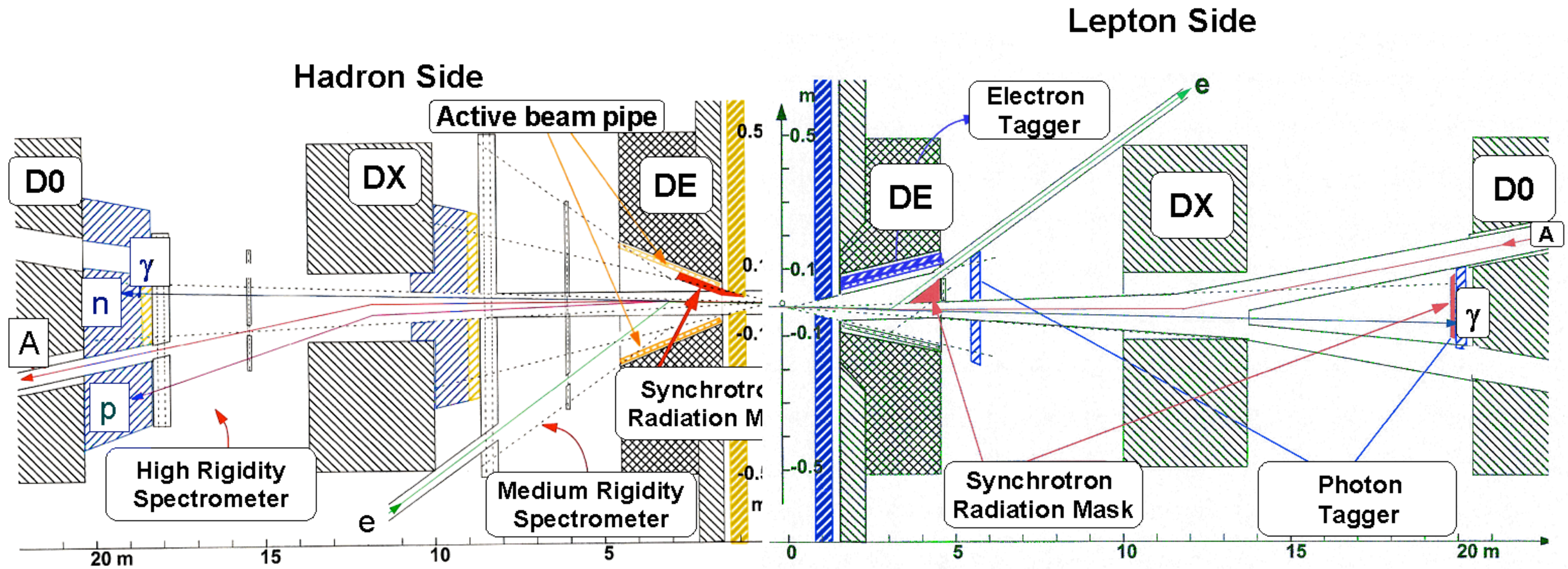
Detector Design (I)… others expected



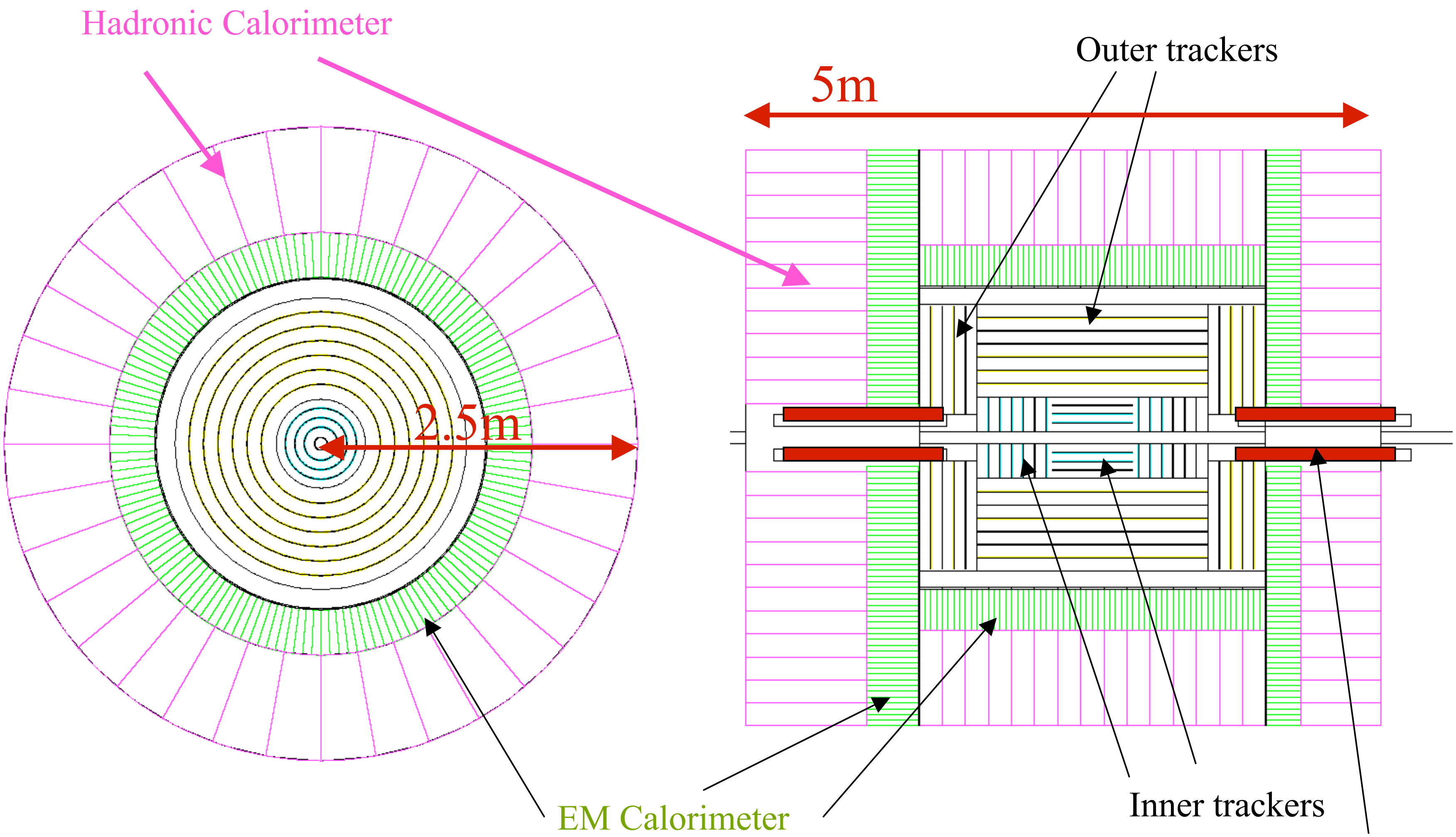
W. Krasny et al.

Detector Design (I)





Detector Design II



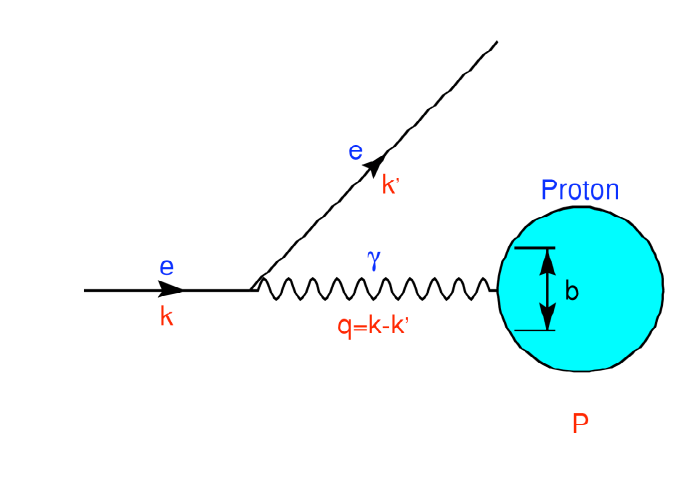
Detector design tool being setup by B. Surrow

Nearest beam elements 1m

Activity in summer 2004 expected

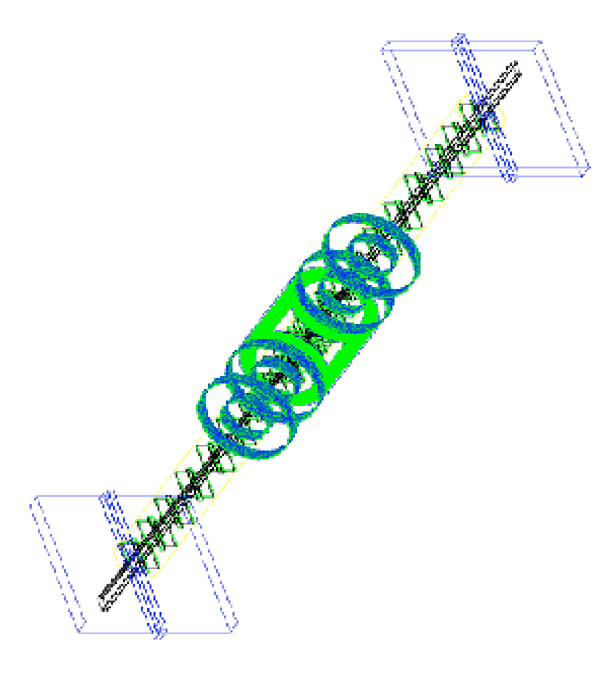
A New Round of DIS Experiments – HERA III/eRHIC

A. Caldwell, Max-Planck-Institut f. Physik /Columbia University

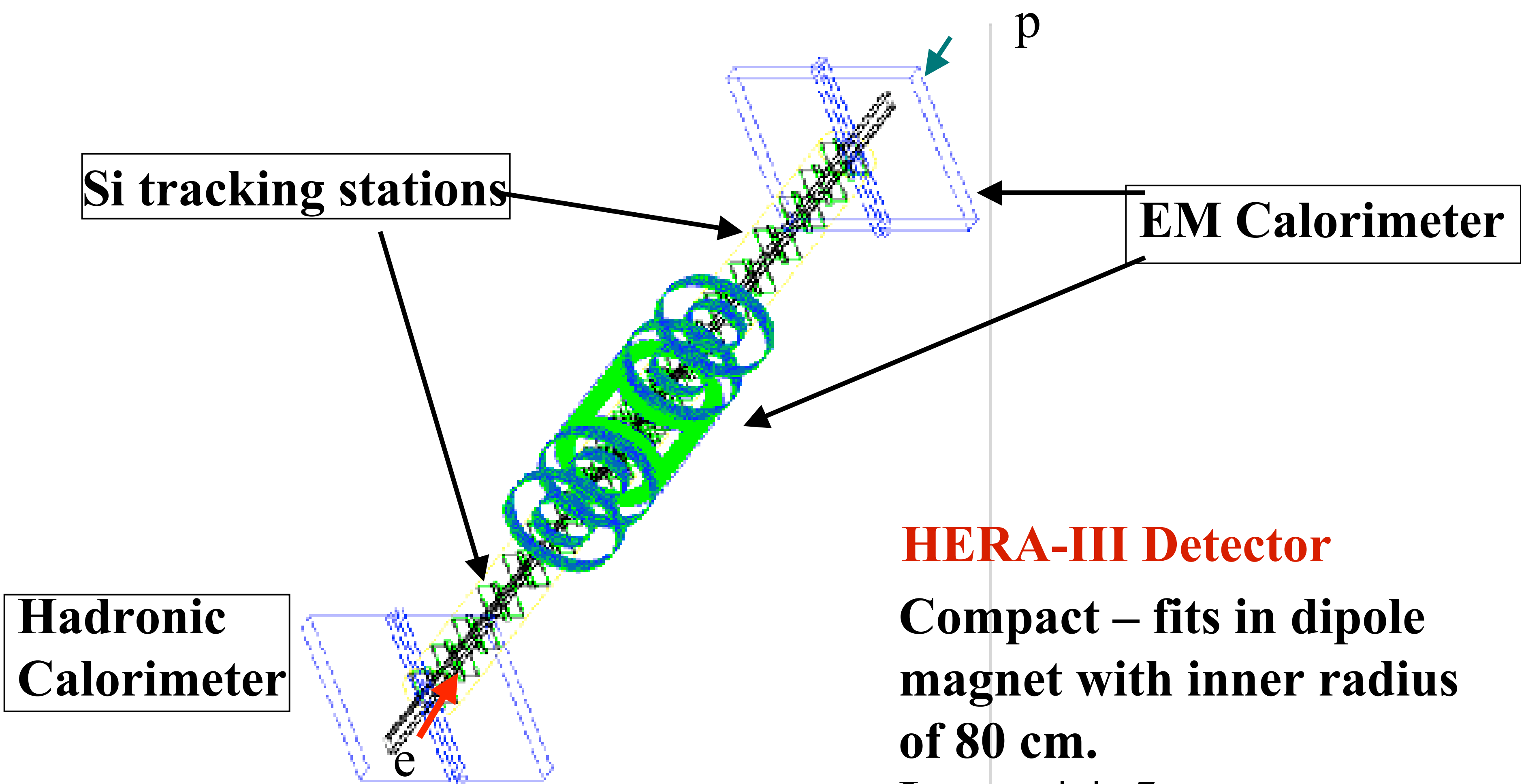


Physics - QCD in the high energy limit

New Detector for HERA/eRHIC
H1 Upgraded Detector



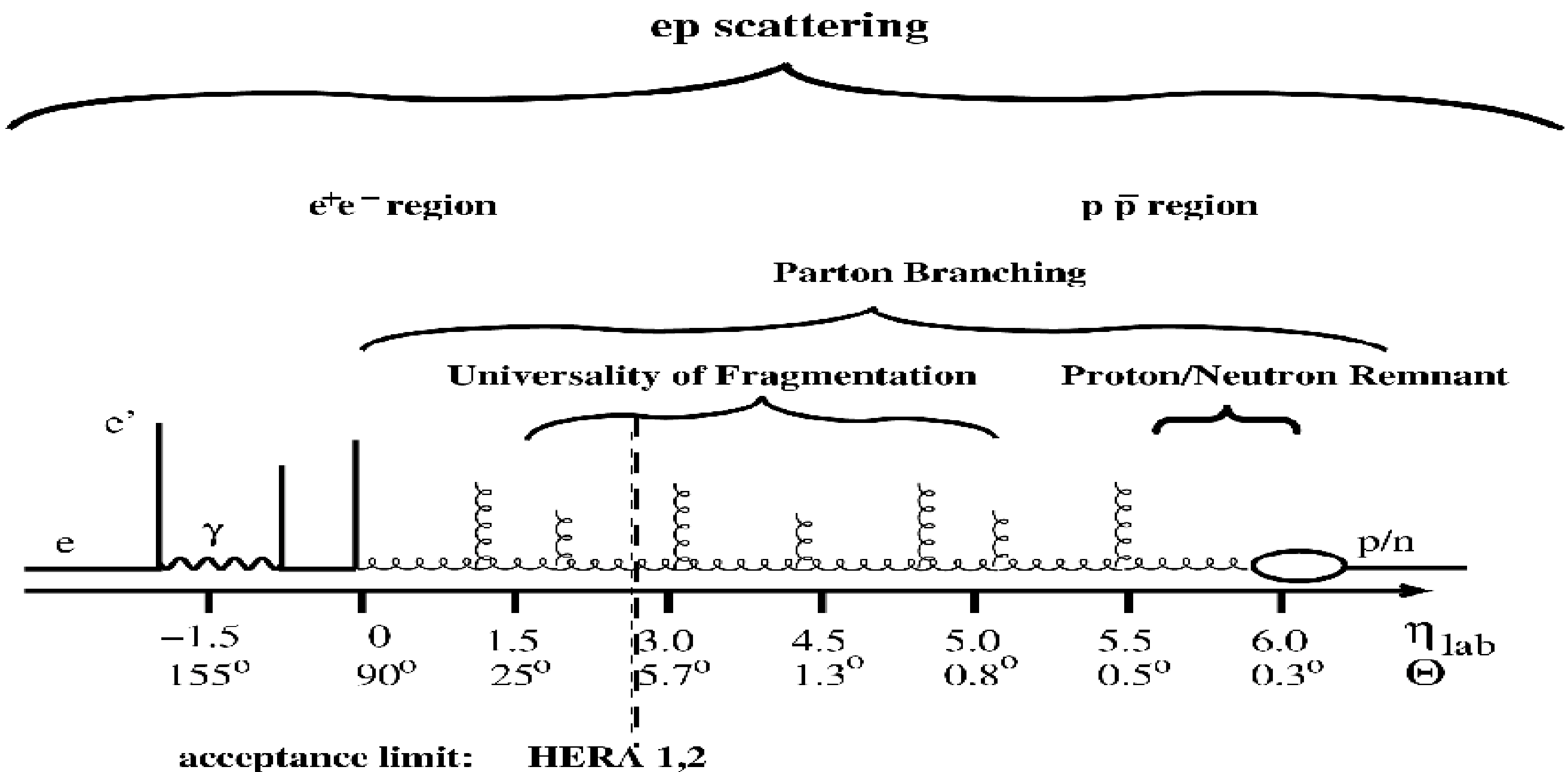
A new detector to study strong interaction physics



HERA-III Detector

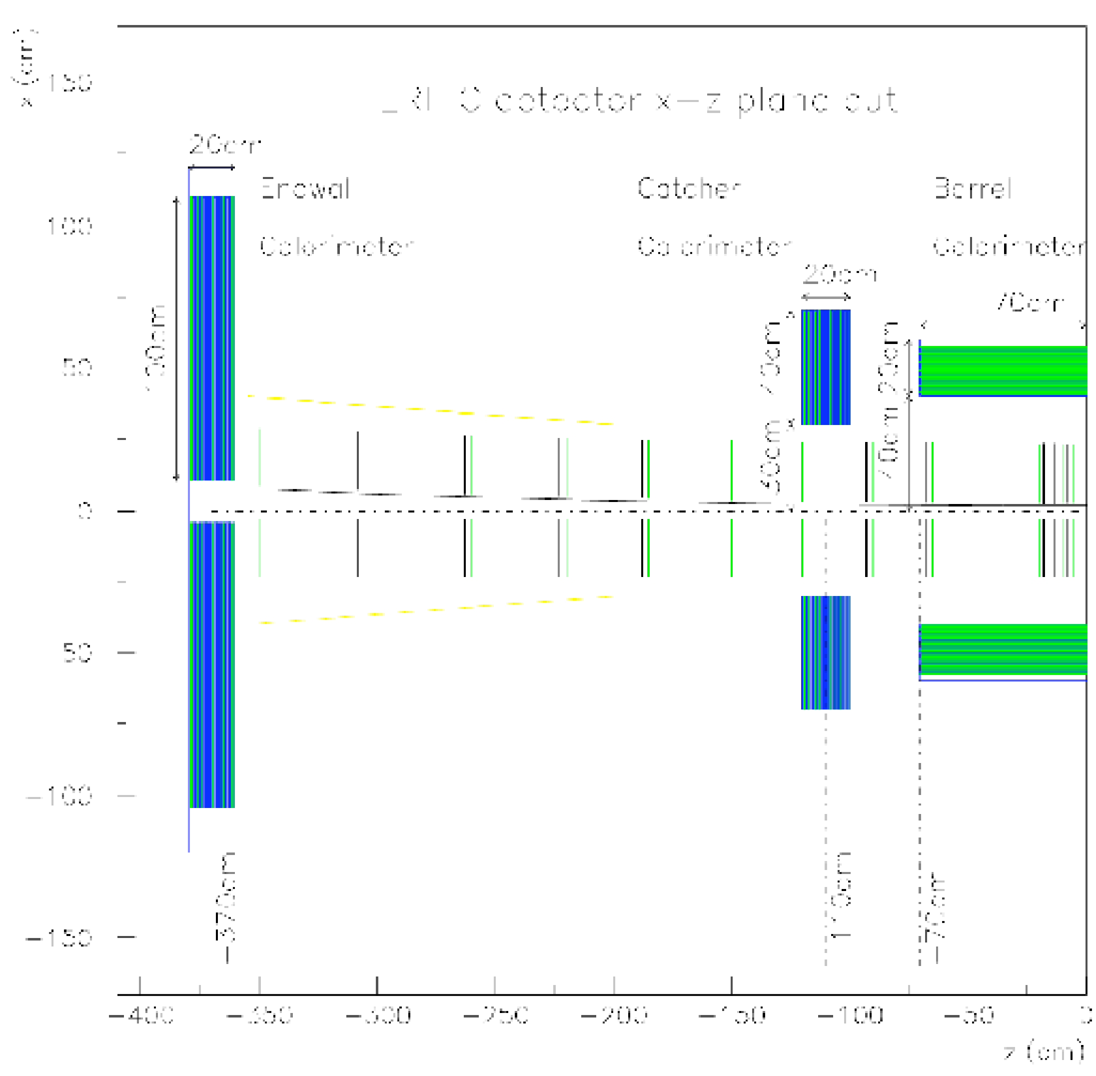
Compact – fits in dipole magnet with inner radius of 80 cm.
Long - |z|≤5 m

Understanding QCD virtual radiation

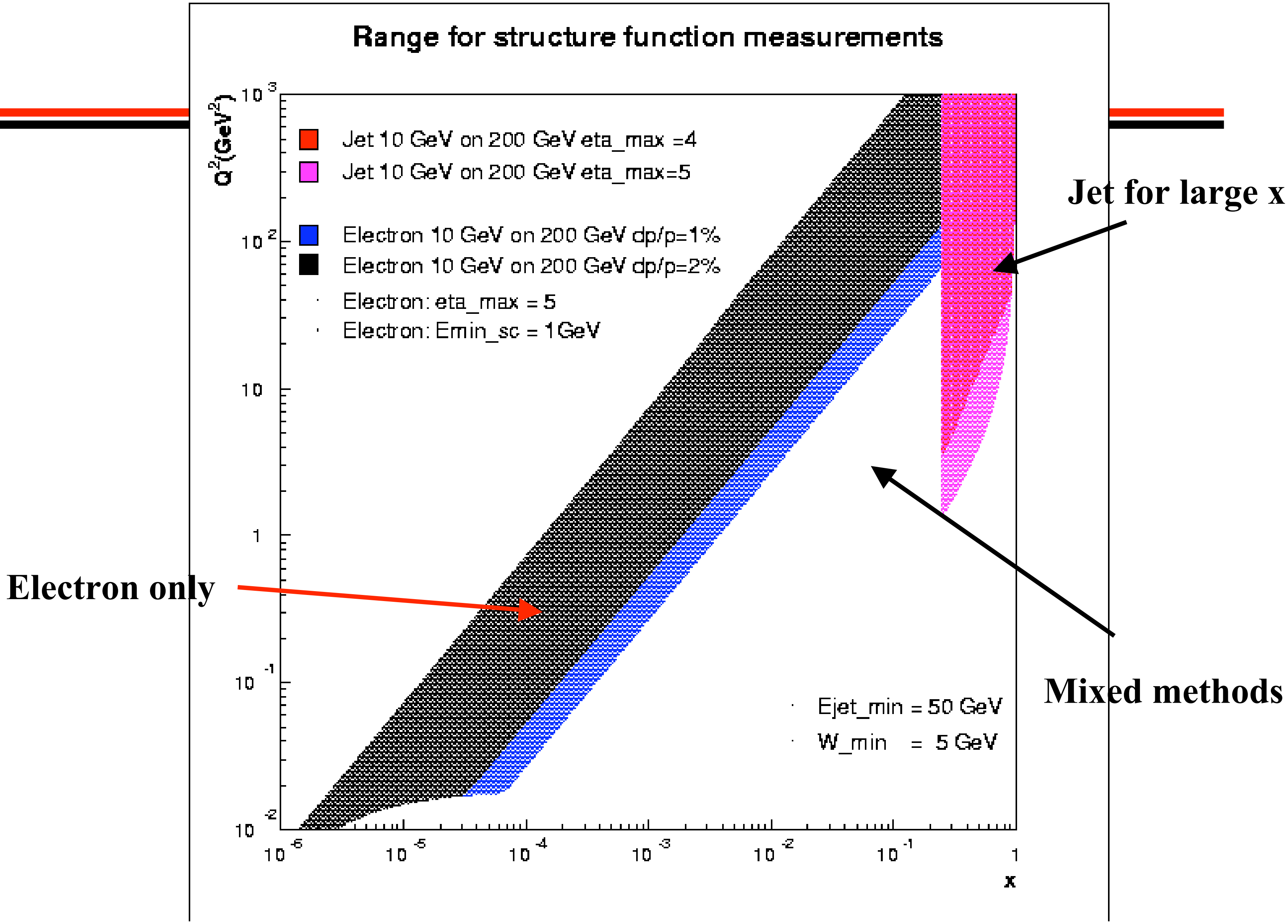


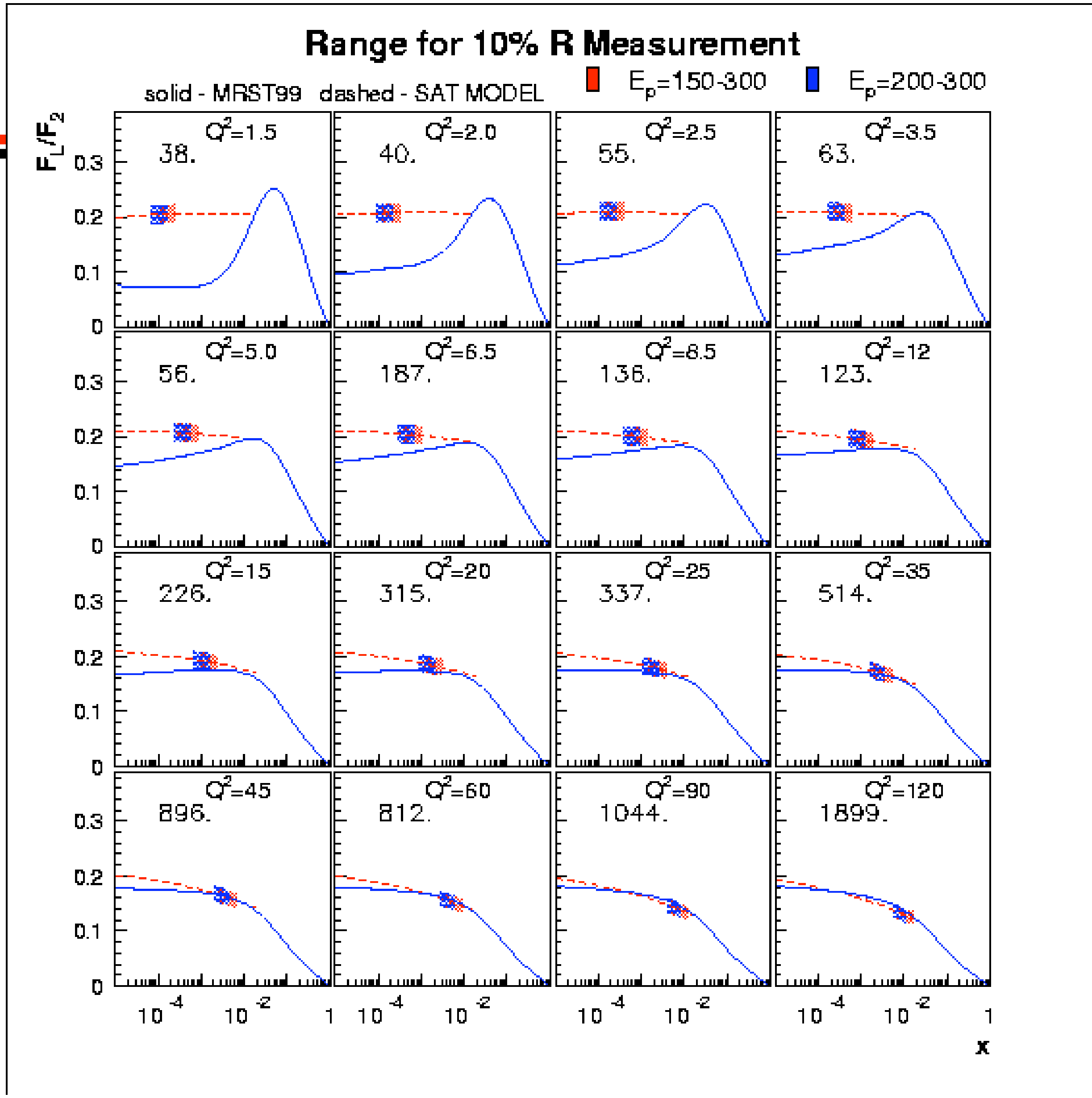
To be measured in future

Physics/Detector studies for eRHIC

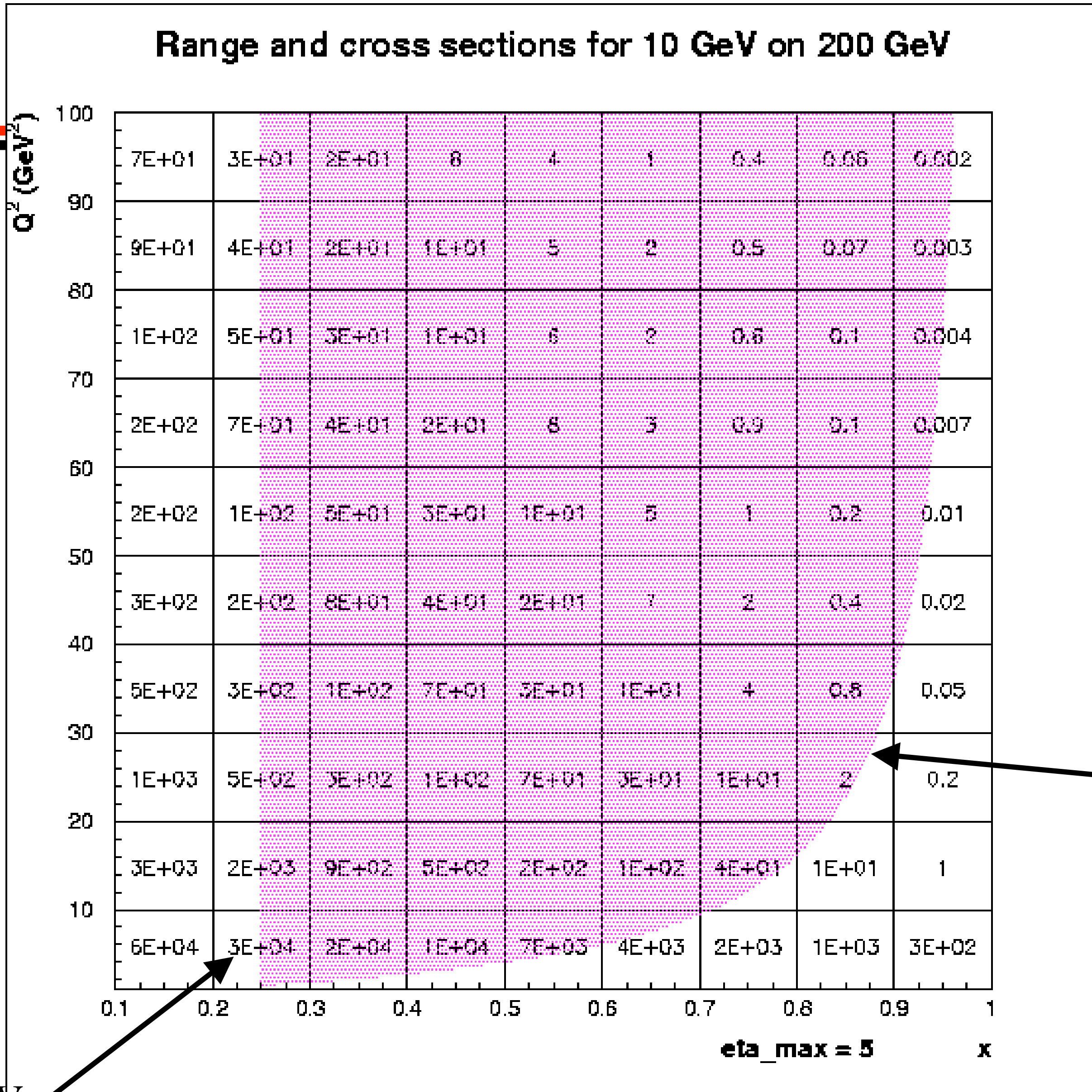


2x14 Si tracking stations


Range for structure function measurements
Jet 10 GeV on 200 GeV eta_max =4
Jet 10 GeV on 200 GeV eta_max=5
Electron 10 GeV on 200 GeV dp/p=1%
Electron 10 GeV on 200 GeV dp/p=2%
Electron: eta_max = 5
Electron: Emin_sc = 1GeV
Ejet_min = 50 GeV
W_min = 5 GeV
$Q^2(GeV^2)$
x
Jet for large x
Electron only
Mixed methods


Range for 10% R Measurement
solid - MRST99 dashed - SAT MODEL
E_p=150-300
E_p=200-300
F_L/F_2
Q²=1.5
38.
Q²=2.0
40.
Q²=2.5
55.
Q²=3.5
63.
Q²=5.0
56.
Q²=6.5
187.
Q²=8.5
136.
Q²=12
123.
Q²=15
226.
Q²=20
315.
Q²=25
337.
Q²=35
514.
Q²=45
896.
Q²=60
812.
Q²=90
1044.
Q²=120
1899.
0
0.1
0.2
0.3
10⁻⁴
10⁻²
1
x

Cross sections in pb



$W^2 > 5\ GeV^2$

$E_{jet} > 50$ GeV

Summary and Outlook

- eRHIC will bring a new & complimentary dimension to the physics being pursued at RHIC
  - Measurements will be unique and essential for the detailed understanding of QCD
  - No other existing or planned facility will have the breadth of physics as eRHIC

- Preparations for eRHIC continue on: expect to get the formal blessing from NSAC LRP 2005/6
- Lots of activities on Accelerator Design, Detector Design and Physics Studies in progress, but lot of untouched territory: "***You are welcome to join!***"